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Roberto Fernández[1,2], Sergi Gallego[1,2], Víctor Navarro-Fuster[2], Manuel Ortuño[1,2], Andrés Márquez[1,2], C. Neipp[1,2], Augusto Beléndez[1,2], Inmaculada Pascual[2,3]

[1]Dept. de Física, Ing. de Sistemas y Teoría de la Señal, Universidad de Alicante, P.O. Box 99, E-03080, Alicante, Spain

[2]I.U. Física Aplicada a las Ciencias y las Tecnologías Universidad de Alicante, P.O. Box 99, E-03080,

Alicante, Spain

[3]Dept. de Óptica, Farmacología y Anatomía, Universidad de Alicante, P.O. Box 99, E-03080, Alicante, Spain

The improving of the technology related to the Spatial Light Modulators (SLM), which can be used to modulate the wavefront of a light beam in many different applications in Optics and Photonics, has widespread their use in many new ways. In particular, the continue miniaturization of the pixel size let them be used as a master for Diffractive Optical Elements (DOE) recording applications. One of these displays is the parallel-addressed liquid crystal on silicon (PA-LCoS) microdisplay, which offers easily the possibility of phase-only modulation without coupled amplitude modulation, but can be use also as an amplitude master just rotating the angles of two polarizers. Together with the DOEs, the optic recording material is also one of the crucial components in the system. Photoresist has been used classically for this purpose. Recently some works provide results of the incorporation of photopolymers, initially used for holographic recording, to fabricate DOEs. Among photopolymers, polyvinil alcohol/acrylamide (PVA/AA) materials have been studied firstly due to the accurate control of their optical properties and the ease of fabrication. Nevertheless, this kind of photopolymer presents a high level of toxicity due mainly to the monomer, acrylamide. In this sense, we made efforts to search alternative "green" photopolymers, one of these is called "Biophotopol". This material presents good optical properties; although, it has two principal drawbacks: its refractive index modulation is lower than the PVA/AA one and the dye used presents very low absorption at 532 nm. In order to solve these problems for recording spherical diffractive lenses, in the present work we have explored different possibilities. On the first place, we have modified the fabrication technique of the solid layer to achieve thicker samples, on the second place, we have introduced a biocompatible crosslinker monomer. These two actions provide us a higher value of the phase modulation capability. On the third place, we have modified the dye to record DOE's with the wavelength of 532 nm and obtain a direct comparison with the results obtained with PVA/AA materials.

Keywords: Diffractive optics, optical recording materials, liquid crystal on silicon displays, photopolymers, parallel aligned, spatial light modulation.

1. INTRODUCTION

Recently, new hot topic is developing in optics very quickly, that is called "Green Photonics". "Green Photonics" combines applications for generating and saving energy, reducing greenhouse gases, efficiently generating light and the use of biodegradable materials. The associated technologies include photovoltaic, light emitting diode illumination, optical sensors, and energy-efficient communication technologies, energy- and resource-efficient laser production processes as well as non-contaminating materials [1-3]. In this sense many efforts have made to substitute the materials involved in optics and photonics application by less contaminating ones. In the field of diffractive and photonics elements fabrication one of the most interesting materials involves polymers. In particular, photopolymers have become one of the photosensitive materials with greater ability to develop systems and photonic devices of considerable interest today. The

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photopolymer recording materials are highly versatile, with respect to their composition, reliability and properties. This makes photopolymers one of the best recording media for holographic storage applications and an ideal candidate for the fabrication of photonic devices such as two-dimensional structures, waveguides, or diffractive optical elements. Applications that have now a great scientific and technological interest, in which context lies this research work [4-5]. One of the main drawbacks of these materials is the elevate toxicity of some component, therefore may efforts were focused in the searching of alternative and "greener" materials. On the other hand, the ability of modulating an incident wave by means of a spatial light modulator makes it possible to generate diffractive optical elements in many applications in photonics, communications, holographic storage or information processing as long as a recording material with suitable characteristics is available, such as photopolymers.

One of the photopolymers widely used in the optics community is the based in polyvinyl alcohol/acrylamide (PVA/AA), with this materials interesting results were presented about the fabrication of blazed gratings [6], spherical lenses [7] or cylindrical ones [8]. Nevertheless, the high toxicity of the main monomer, acrylamide, pushes us to find biocompatible photopolymer formulations with similar optical properties. One of the best candidates is the photopolymer called "Biophotopol" [9] however, the dye of this materials is less sensitive to record elements at 532 nm, therefore we used this formulation changing the dye by yellowish eosin, that presents maximum absorption near this wavelength. As the refractive index modulation capability of this compound is slightly smaller than PVA/AA [10] we have modified the technique of the layer fabrication in order to increase the thickness of the film, thus the phase depth can be greater than 2π. In this work, we present the preliminary study of the recording of spherical lenses with different focal lengths in this biocompatible photopolymer and compare the results with those obtained by PVA/AA.

2. EXPERIMENTAL SET-UP

The composition of the photopolymer was prepared by adding yellowish eosin (YE) together with sodium acrylate (AONa) and triethanolamine (TEA) to 35 ml of poly(vinyl alcohol) (PVA) as binder (Mw = 130,000, hydrolysis degree = 87.7%). We also added 87 g of *N*,*N*'-(1,2-dihydroxyethylene) bisacrylamide (DHEBA) used as a crosslinker.

About 4.5 g of the resulting solution was deposited on 6.5 x 6.5 cm^2 glass plate using the force of gravity and left inside a dark incubator (Climacell 111) with controlled humidity and temperature (Hr = 60 ± 5% and T = 20 ± 1 ºC, respectively). When part of the water had evaporated (drying time 24h), the "solid" film thickness decreased to 250 μm. At this time, the plate was then ready for exposure. The thickness of the solid film was measured using an ultrasonic pulse-echo gauge (PositTector 200) after exposure.

In previous experiments, the photopolymer was composed by acrylamide (AA) as polymerizable monomer, N,N'-methylene-bis-acrylamide (BMA) as crosslinking monomer, triethanolamine (TEA) as coinitiator and plasticizer, yellowish eosin (YE) as dye, polyvinyl alcohol (PVA) as binder and a small proportion of water as additional plasticizer. Different types of PVA can be used as binder. In this work, we have used a PVA 18-88 with Mw= 180000 amu. The final "solid" film has a physical thickness around 90±5 μm [7].

We used a hybrid digital-optical experimental set up presented in Figure 1 [9]. The diffractive lenses are projected onto the material using a last generation spatial light modulator based on Liquid a Cristal on Silicon (LCoS) microdisplay working in the amplitude mode. This setup is both used to register and analyze the diffractive optical lenses. The recording process uses the wavelength 532 nm, and the lenses are calculated to be used with the 633 nm wavelength. The system is designed to measure the performance of the lenses in real-time, while the recording process is taking place. We distinguish two arms: the recording arm, using the wavelength 532 nm provided by a solid-state Verdi laser (Nd-YVO4) with recording intensity of 0.5 mW/cm^2, and the analyzing arm, using the wavelength 633 nm, to which the material presents no absorption, provided by a He-Ne laser. In the recording arm we place the LCD sandwiched between two polarizers (P), which are oriented with the appropriate angles (45º for the first one and -45º for the last one) to produce amplitude-mostly modulation with a contrast of 20. Then, a 4F system is used to image the intensity transparency displayed on the reflective LCD onto the recording material. To generate the diffractive lenses, we use an LCoS-Pluto provided by Holoeye with a resolution of 1920x1080 (HDTV) pixels and a pixel size of 8x8 μm^2, previously characterized [11]. We have projected lenses with three different focal lengths: 13 cm, 54 cm, and 116 cm. The analyzing arm is designed so that the beam of light incident onto the recording material is collimated. D1, a diaphragm, is used to limit the aperture of the collimated beam. We need to introduce a non-polarizing beam-splitter to make that both beams of light, the recording and the analyzing, follow the same path. After the recording material, we have introduced a red filter so that the light incident onto

the final CCD camera is only coming from the analyzing beam. The lens recorded on the photopolymer is responsible for the focusing of the 633 nm wavelength beam. We imaged the point spread function (PSF) generated by the diffractive lens onto the CCD camera. We can control the magnification of our experimental set-up using a 4-F system by the focal lengths of L3 and L4. We used a high dynamic range CCD, which is necessary to appreciate details in the PSF. This CCD camera model is pco.1600 from pco.imaging. A high dynamic 14 bits cooled CCD camera system with a resolution of 1600x1200 pixels and a pixel size of 7.4x7.4 μm^2. The camera is also used on the plane of the recording material to evaluate the intensity pattern actually imaged from the LCoS plane.

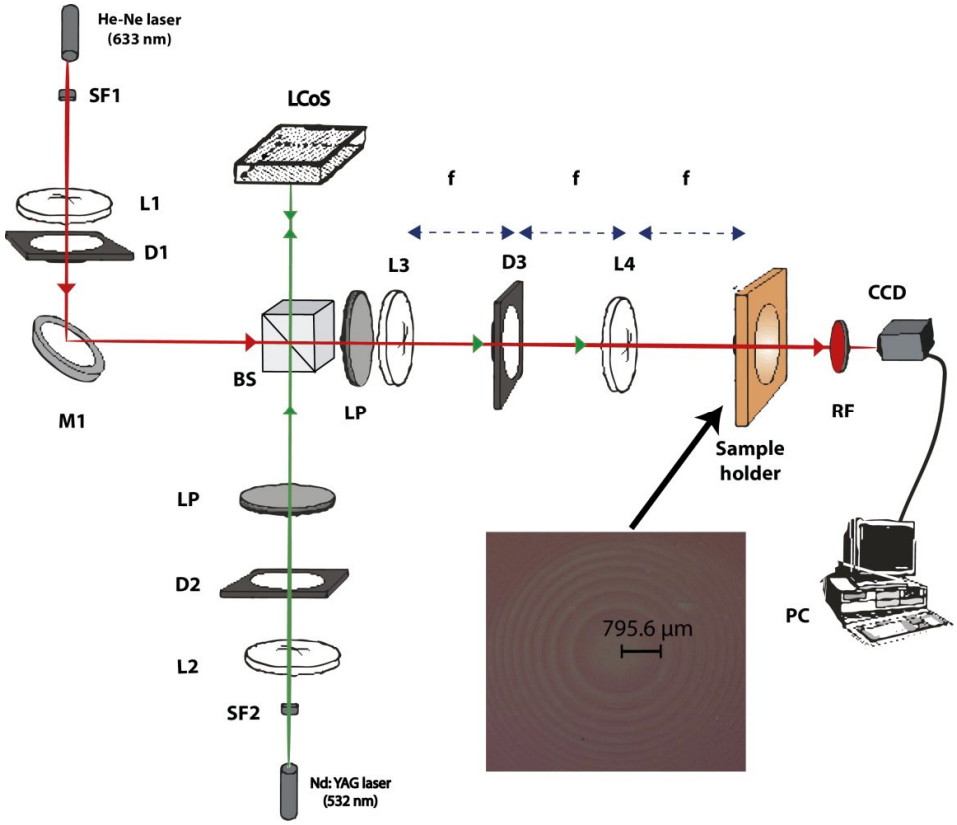

Fig. 1. Experimental setup used to register and analyze in real-time the DOEs (diffractive lenses) D, diaphragm, L, lens, BS, Beam splitter, SF, spatial filter, LP, lineal polarizer, RF, red filter.

The recording intensity distribution from the spatial light modulator in the amplitude regime is projected on the material, producing the corresponding phase element. In particular, in the case of the spherical lens with focal f, we need to generate a convergent spherical wave front, where the phase depends on the quadratic value of the distance between the point and the lens centrum, thus we want to obtain at the first attempt can be write as:

$$I(x,y) = \exp\left[j \frac{\pi}{\lambda f} \left(x^2 + y^2 \right) \right] \tag{1}$$

To obtain this phase distribution we assume a linear response of the recording material concerting an amplitude distribution generated by LCoS into a phase distribution. Therefore Eq. 6 has to be wrapped to 2π value and normalized to the maximum of the intensity, I0. In this sense, for f=1m when we imaged an amplitude distribution with a maximum intensity in the middle and there are a series of rings of zeros located at:

$$r_m = \sqrt{m(2\lambda f)} \tag{2}$$

Where m is a natural number, f is the focal length and λ is the light wavelength. Moreover, we know that the maximum phase shift achieved for photopolymers at these spatial frequencies range is slightly higher than 2π. Therefore, we have to wrap the phase as is depicted in Fig. 2; this desired intensity distribution is generated using a LCD.

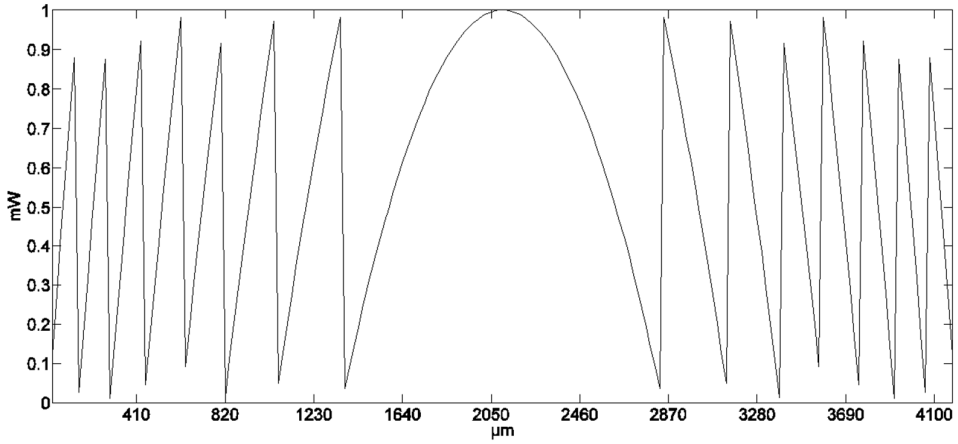

Figure. 2 Theoretical intensity distribution (horizontal cut) projected onto photopolymer for a focal length of 13 cm.

In Fig. 3.a, we show the image obtained using the CCD camera when it is placed in the recording plane. We see the characteristic structure with decreasing period as we move away from the center of the diffractive lens. In Fig. 3.b, we show the intensity plot along the horizontal line passing through the center of the lens. This intensity pattern in Fig. 3 is the exposure pattern that will be recorded on the photopolymeric material. This new spatial light modulation is composed by square pixel of 8 μm^2 that provides the opportunity of recording symmetric and asymmetric intensity patterns using a single beam [7-8], or alternative diffractive optical elements with more resolution. Nevertheless, we can see some important differences between Figure 2, ideal intensity distribution, and Figure 3 due to the finite size of pixels and the low pass filtering of the optical set-up, these differences are more accused in the boundaries of the lens where the distance between two consecutive peaks is smaller. In particular, for values smaller than 250 pixels and higher than 800 pixels we only appreciate a peak without any concrete shape, it is important to remark that also the maximum of the peak varies more than 50%, maybe due to the finite size of the camera pixel. In any case it is very important have a homogenous illumination of the LCoS in order to avoid this problem.

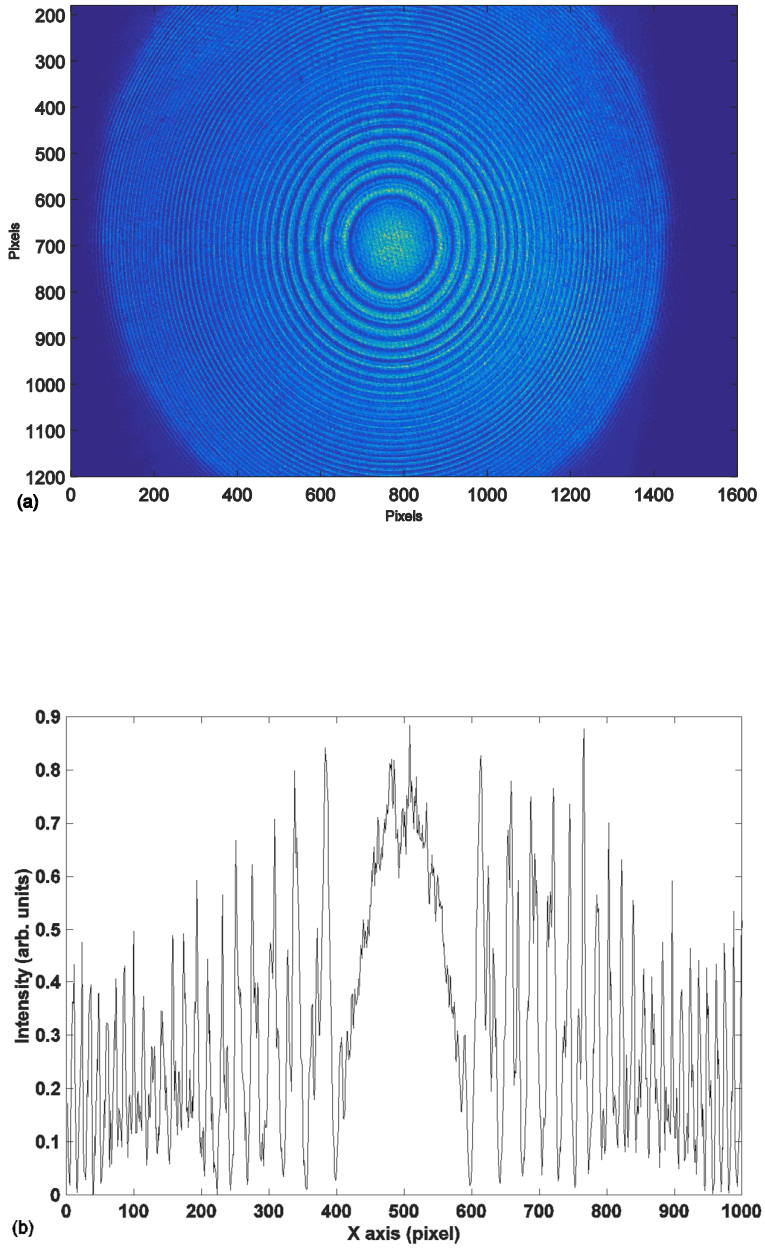

Fig. 3. (a) Image of the LCoS at the material plane (where the intensity transmittance equivalent lens is displayed) captured by the CCD camera. This plane is where the photopolymer should be placed. (b) Intensity profile across the horizontal line passing through the center of the projected intensity distribution to record lenses with 13 cm of focal length.

With lenses with higher values of the focal length such as 116 cm, the profile of the recording intensity is more accurately defined. On the other hand, less number of rings can be illuminated using the same recording beam.

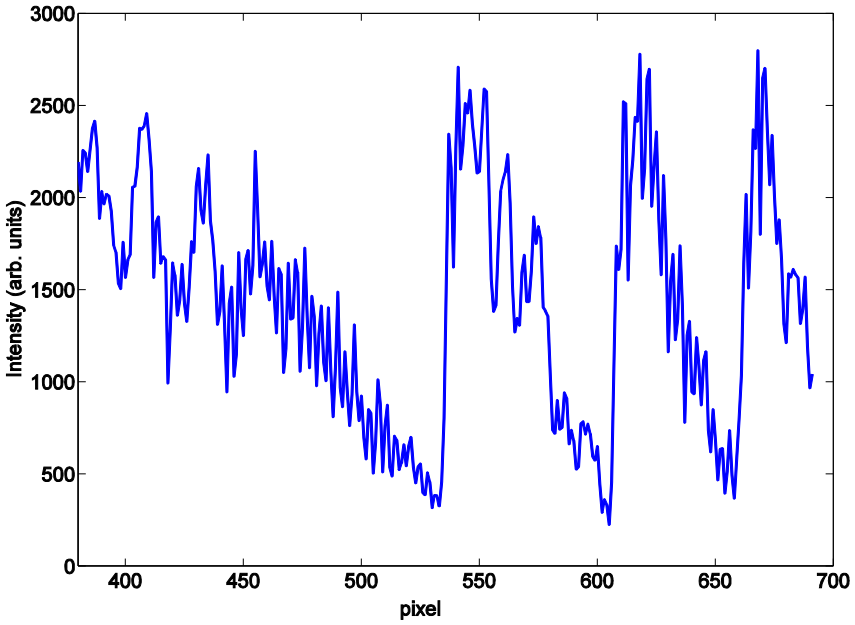

Fig. 4. From the center of the lens along a radial line at the material plane captured by the CCD camera, focal length 116 cm

3. RESULTS AND DISCUSSION

Considering previous results of the diffractive lenses fabrication in PVA/AA photopolymers and the comparison at zero spatial frequency limit as well as sinusoidal gratings fabrication with Biophotopol, we expected that the phase depth of 2π can be achieved really fast. To analyze the formation of the lens in the photopolymer, we placed the CCD camera just in the focal plane. In Figure 5.a, we present the evolution of the intensity of the focal point as a function of the recording time, 80 s, for Biophotopol polymer. After 80 s, the recording laser, green one, is switched off, and we can see the conservation under red light (to which the dye does not present absorption). The intensity of the focal point starts growing very fast until 15s of exposition, then begins to slow down with some irregularities. The maximum intensity is achieved after 38 s of recording time. From this point, we observe a small defocusing effect, maybe due to the overmodulation, the phase depth, slightly larger than 2π, or an increment of the noise, losing the 20% of the intensity after 60 s of recording time. Between 60 s and 80 s, any huge change can be detected; maybe the material is near saturation. When the recording process stops, the focal intensity keeps constant. This is a good property in order to record stable DOE. In Figure 5.b, we present the results obtained by PVA/AA materials, where similar results are obtained using thinner layers, due to the higher value of the refractive index modulation. Biophotopol presents optimum energetic behavior; the maximum is achieved with less radiation dose. On the other hand, the magnification of the intensity at the focal point is higher for PVA/AA materials.

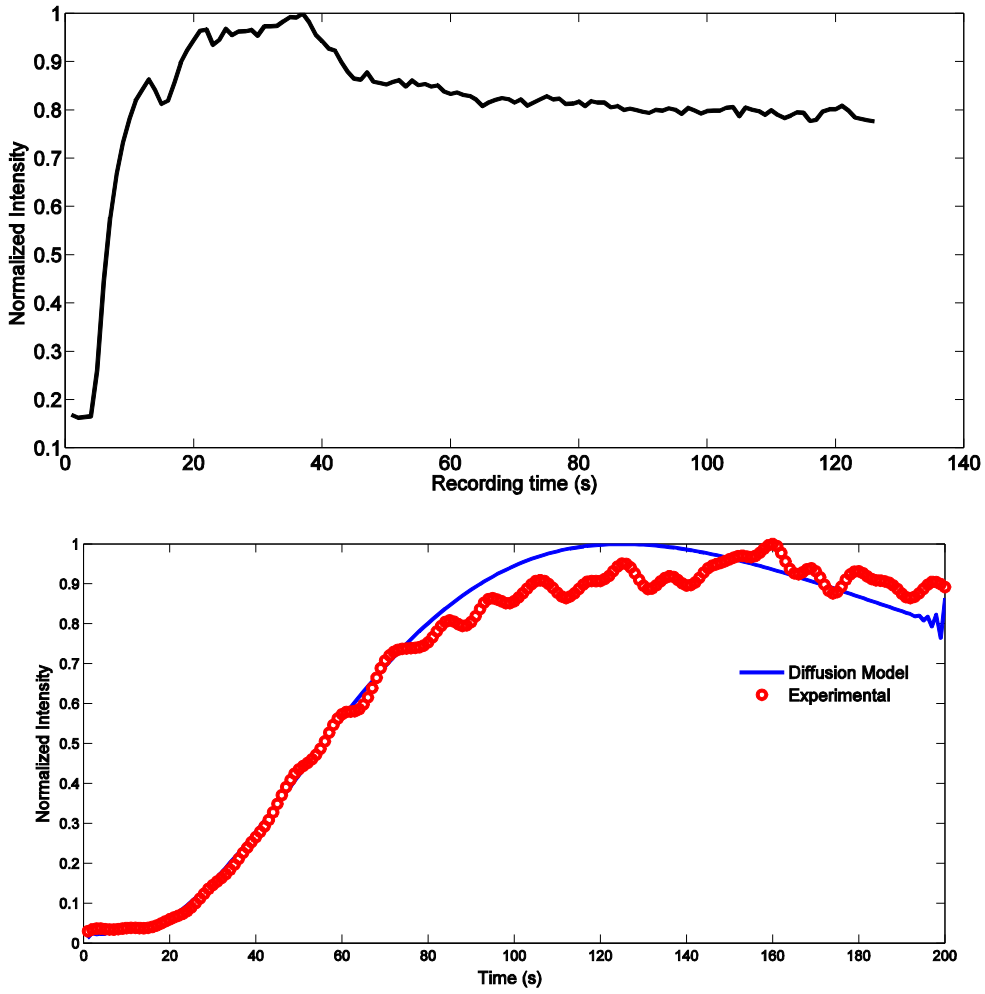

Figure 5. – Intensity measured at the focal point using He-Ne laser for f=0.53 m (a) Biophotopol, layer thickness of 250 ±5 µm, (b) PVA/AA layer thickness of 95±2 µm..

In Figure 6, we depicted the intensity distribution captured by CCD camera at the focal point for recording times: 5, 20, 40, and 80 s. From Figure 6, we can see the good focalization of our recorded lens; nevertheless, this focalization is not perfect, there is a small asymmetry. Diaphragm 1 let us to eliminate the effect of the pixilation in the projected image, but on the other hand, smooths our image. In the case of diffractive lenses, this effect is especially important due to the sharp profiles required. Nevertheless, as it can be seen, the red light begins to be focalized around the focal point, and the intensity of this area is growing very fast during the first 20 s and 40 s to arise a maximum value for this exposition time. We did not detect important differences between different focal length, but we are still analyzing the influence of the focal length in the quality of the point spread function.

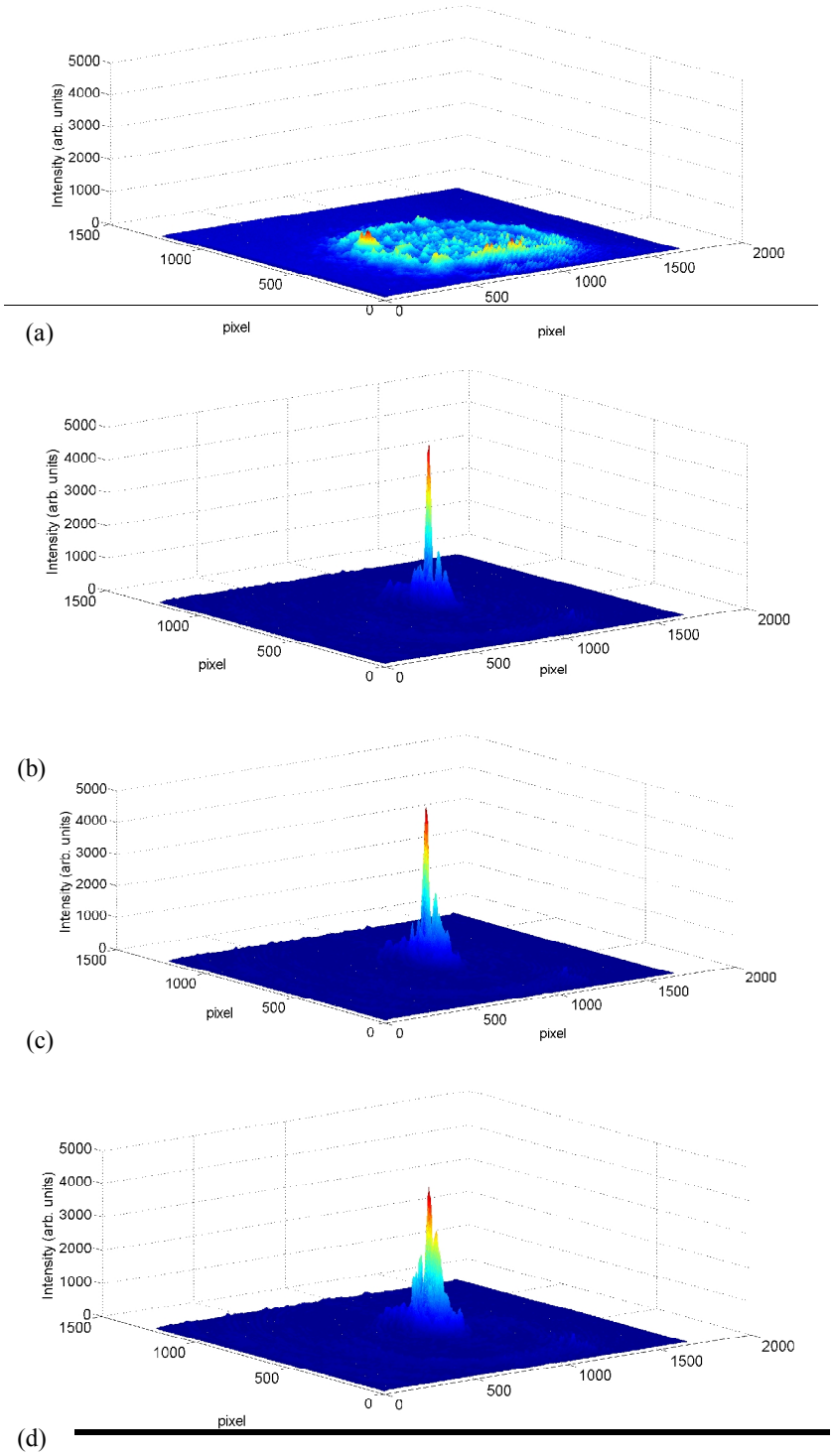

Figure 6.- Intensity distribution at the focal plane (a) 2 s, (b) 20 s, (c) 400 s, (d) 60 s.

4. CONCLUSIONS

To summarize, we have presented the fabrication of diffractive lenses onto high biocompatible photopolymers with good focusing power. Firstly, we have shown as the optimum recording time for the recoding intensity of 0.5 mW/cm^2 is around 38 s. After this time, the intensity focused in the focus line decreases even 20%. We have demonstrated how the lenses present good conservation after recording. Comparing with PVA/AA photopolymers, Biophotopol need less energy to achieve the maximum focalization, but this is less than the measured for PVA/AA materials. Additional studies will be developed to optimize the fabrication of diffractive lenses in Biophotopol

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